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NON-METALLIC MAGNETIC MATERIAL FOR HIGH FREQUENCIES

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621.318.323.2: 538.245

It is a well-known phenomenon that when an a.c. field is generated in metallic coils eddy currents are set up in the core. The resultant loss of energy can be minimized, in the case of low frequencies, by using a laminated core with insulation between the plates. The higher the frequency, however, the finer the distribution of the core laminations has to be, and as a matter of fact for rather high frequencies cores are being used that are made up of wire and even grains (so-called dust cores); in the latter kind the lines of force run in part through the non-magnetic insulation of the grains, so that there is always a fairly large minimum "air-gap".

Entirely new methods have become possible as the result of researchwork with ferrites, substances of the type of MFe_2O_4 , with M denoting a bivalent metal. Some of these ferrites have a cubic structure and are capable of forming mixed crystals in any proportions. With a few exceptions these non-metallic substances are ferromagnetic. Their specific resistivity is 10^7 - 10^{12} times as high as that of iron, so that the problem of eddy currents is relegated entirely to the background, even in the range of radiofrequencies and without laminations. By suitable composition and heat treatment it is also possible to keep the hysteresis and residual losses relatively low, whilst the initial permeability may be of the order of 1000. By means of a pressure or spraying process this material, called "Ferroxcube", can be moulded into various shapes, and coils of improved quality or smaller volume have been made with it for different purposes. Thanks to its being homogeneous it makes a good magnetic screen.

Metallic and non-metallic ferromagnetics

Magnetic properties were most probably discovered in non-metallic substances much sooner than in metals. Anyhow magnetite (magnetic iron ore, Fe_3O_4) was known in ancient times as a non-metallic ferromagnetic mineral.

It was not until the nineteenth century that any real technical use was made of these magnetic properties, except for compasses. And when, following upon the epoch-making discoveries of Faraday and others, an electrotechnical industry sprang up and a demand arose for suitable magnetic materials, it was not these minerals that were sought but rather iron or alloys with iron as basic component; magnetic oxides were considered to be nothing more than a scientific curiosity.

When it came to using metallic cores in magnetic alternating fields one very soon came up against the phenomenon of eddy currents discovered by Foucault, and the losses due thereto. In order to reduce these losses one proceeded to laminate the cores; this offered the additional advantage that

the plate-shaped material could be properly purified by annealing, thereby improving its magnetic properties. By simple deduction one can arrive at the following formula for the eddy current losses W_e of a laminated core (assuming the magnetic induction to be equal at all points of a core section):

$$W_e = \frac{4}{3} (af B_{\max})^2 \cdot \frac{d^2}{\rho} \cdot V \cdot 10^{-16} \text{ watt} \quad (1)$$

Here f is the frequency in c/sec., $B_{\max}$ the amplitude of the magnetic alternating induction in gauss, d the thickness in cm, ρ the specific resistance of the core material in ohm. cm, V the volume of iron in cm^3 and a the so-called form factor, which in the case of an induction sinusoidally variable with time amounts to $\pi/2\sqrt{2} = 1.11$.

This formula shows that there are only two ways of reducing eddy current losses for a given frequency and induction, viz:

- 1) by reducing the plate thickness (d);
- 2) by increasing the specific resistance (ρ).

The thinner the sheet is rolled from which the core plates are punched or cut out, the better it will be purified by the subsequent annealing, but on the other hand this means increased cost of manufacture, more time in stacking the plates to form a core of certain dimensions and more loss of space owing to the necessary insulation between the laminations. As a result it is found that there is a certain limit for the optimum plate thickness, which for the frequencies of the electric light and power mains (40-60 c/sec) lies between 0.5 and 0.3 mm.

To a certain extent the building-up of cores out of laminated material has its attractions for the coil-maker, because cores of different sizes can be made with identical parts simply by varying the number of plates going to make up the stack, but this method costs time, a factor that counts particularly in mass manufacture. There is no doubt, therefore, that if it were possible from the point of view of eddy current losses, it would in many cases be preferable to employ solid cores such as can now be made in sufficient purity by the modern methods of refined melting.

As to the second method of reducing eddy current losses, by increasing the specific resistance, in spite of extensive metallurgical research it has not been possible to find magnetic iron alloys with a specific resistance higher than about five times that of pure iron, which is 10^{-5} ohm. cm. Although even this figure was a considerable step forward, it was by no means sufficient to satisfy the requirements of modern developments in telephone and radio technology with their so much higher frequencies accentuating the problem of eddy current losses.

Consequently — still holding fast to metallic cores — one was obliged to go farther in the direction of a finer distribution of the core material, and as a result so-called dust cores were introduced, consisting of fine grains of metal enclosed in an insulating envelope and compressed into a conglomerate of the greatest possible density. The cost of manufacturing such a finely divided powder is only a fraction of that of laminations of a thickness equalling the diameter of the grain. To draw a wire of that diameter would be still more expensive.

It was, of course, realized right from the outset that the introduction of powder cores involved a considerable loss of permeability, since the numerous granules are separated by insulating layers acting magnetically as "air-gaps". Every endeavour has been made to minimize this drawback, and not without some degree of success, as will appear from what follows.

Loading coils with a core composed of metal

granules 50 microns and less in diameter have been developed for frequencies up to 3000 c/sec, and with an effective permeability of the core material as high as 125. From this it can be calculated that less than $1/125 = 0.008$ of the total length of the lines of force is occupied by non-magnetic material, so that the thickness of the insulating envelope around the grains is less than $0.008 \times 50 = 0.4$ micron (presumably about 0.2 micron). To attain such a result as this an extremely refined technique had to be developed for applying such thin layers to the grains, and it is obvious that any further appreciable improvement in this direction can hardly be expected.

In order to limit eddy current losses sufficiently for the so much higher frequencies used in radio-technics, the size of grain had to be very drastically reduced, thereby taking into the bargain, of course, a further diminution of effective permeability.

It is not surprising that in the course of these developments the idea frequently occurred to try a different tack altogether and to replace the iron or nickel alloys by non-metallic substances, such as certain magnetic iron oxides having a very high specific resistance. In fact there are two patent specifications of Hilpert dating from 1909 concerning the use of ferrites for ferromagnetic coil cores for high frequencies. The specific resistances of 10^5 - 10^7 ohm cm. quoted as the maximum values for these ferrites contrast strongly with those of the usual metallic core materials, for which only with great difficulty a figure of $5 \cdot 10^{-5}$ ohm cm. has been reached. The gain to an amount of a factor 10^{10} - 10^{12} when using ferrites is quite sufficient to relegate the problem of eddy current losses entirely to the background, but notwithstanding this fact the results do not seem to have been encouraging; at least nothing further has been reported in that respect.

In 1933 Philips laboratories started an investigation into the magnetic properties of ferrites¹⁾, and it was found that the ferrites mentioned by Hilpert do indeed have rather unsatisfactory properties, viz:

- 1) low initial permeability (not much over 10),
- 2) inconsistency in results,
- 3) still rather high total losses notwithstanding the negligible eddy current losses.

Nevertheless Philips' investigations were continued and it has now in fact been found possible to make ferrites with favourable magnetic pro-

¹⁾ See J. L. Snoek: New developments in magnetic materials. Elsevier Publ. Co., New York and Amsterdam, 1946.

perties. But first of all let us consider what ferrites actually are, so as to make it clear presently in what direction this solution had to be sought.

What are ferrites?

Ferrites are understood to be substances answering to the formula MFe_2O_4 , in which M represents a bivalent metal. Ferrous-ferrite Fe_3O_4 (the magnetite previously mentioned), cupri-ferrite, $CuFe_2O_4$, lead-ferrite, $PbFe_2O_4$, etc. are already known, and in the beginning of this century these substances were regarded rather as the salts of an acid, $HFeO_2$, and bivalent metals.

Some of these ferrites are cubic in structure, a point of great importance in view of the fact that a high temperature, 1000-1400 °C, is required for their manufacture, to which we shall revert later. It is in fact only with the cubic structure that shrinkage during cooling is equal in various directions, so that with a substances of a cubic structure cooling need not cause internal stresses. At the time when this investigation into the properties of magnetic oxides was begun, it had just been made apparent from the theories of Kussmann, Becker and Kersten that the absence of stresses was an essential condition for high initial permeability and low hysteresis losses. Consequently investigations were confined to ferrites of the cubic system.

Conditions for obtaining ferrites having favourable properties

Condition for a cubic structure

According to Goldschmidt's crystallographic research the crystal structure depends, *inter alia*, upon the diameters of the ions, and this is borne out by the fact that from cubic Fe_3O_4 other likewise cubic ferrites can be derived when the bivalent ferro-ion is replaced by a bivalent ion of approximately the same diameter as the ferro-ion. This essential condition is not always sufficient, however, to guarantee a structure that is stable also at room temperature. Cupri-ferrite ($CuFe_2O_4$), for instance, has the tendency upon cooling to assume a tetragonal structure; though by rapid cooling from 900 °C downwards it is possible to keep this ferrite in its cubic form at room temperature. Such quenching, however, leads to internal stresses and possibly even to fracture, so that for our purpose cupri-ferrite is of no use.

A table of the radii of ions shows what bivalent ions can be considered for replacing the ferro-ion in Fe_3O_4 , and below in *table I* the radii of these ions are given, together with the radius of the ferro-ion for comparison.

Table I

Metal	Radius of the bivalent ion
Iron	0.83
Magnesium	0.78
Manganese	0.91
Cobalt	0.82
Nickel	0.78
Copper	0.83
Zinc	0.83
Cadmium	1.03

For so far as is known, the ferrites of the metals listed in this table form mixed crystals in all proportions, and these mixed crystals can also be considered for our purpose. The ferrites of the two last-named metals, zinc and cadmium, occupy a very special place, as will be explained below.

Details of the structure of ferrites ²⁾

As shown from a röntgenographical investigation by W. H. Bragg ³⁾, an elementary cell of a ferrite consists of eight molecules, this being expressed, in the case of ferro-ferrite for instance, by the formula $Fe_8^{2+} Fe_{16}^{3+} O_{32}^{2-}$, in which the charges of the atoms present in the form of ions is indicated at the same time.

Owing to their negative charge the oxygen ions are much larger than the positively charged metal ions. They form a cubic system of spheres. In a part of the interstices of this oxygen lattice are the metal ions, arranged in a manner characteristic of the structure. In ferrites these metal ions are arranged like the magnesium and aluminium ions in the mineral spinel, $MgAl_2O_4$, for which reason one speaks of the spinel structure. Now between the oxygen ions in this structure there appear to be two kinds of positions in which the metal ions may be found, namely so-called tetrahedral interstices, each bounded by four oxygen ions located at the corners of a tetrahedron, and so-called octahedral interstices bounded by eight oxygen ions forming an octahedron. In each elementary cell there are 8 tetrahedral — and 16 octahedral — places occupied by metal ions. In spinel it is most probable that the 8 tetrahedral spaces are all occupied by magnesium ions and the 16 octahedral spaces by aluminium ions.

It might then obviously be assumed in the case

²⁾ A more extensive article on the structure of ferrites and allied compounds, which are also of electrotechnical interest, will be published shortly in this periodical.

³⁾ Phil. Mag. 30, 305, 1915.

of the ferrites that the 8 bivalent metal ions occupy the 8 tetrahedral spaces and the 16 ferric ions the 16 octahedral spaces, but a closer examination reveals that this is only the case with two of them, zinc ferrite, ZnFe_2O_4 , and cadmium ferrite, CdFe_2O_4 ; in all other known ferrites the bivalent metal ions and the ferric ions are distributed among both kinds of interstices. This surprising fact is of great importance in more than one respect.

Condition for the occurrence of ferromagnetism; "Ferroxcube".

Zinc ferrite and cadmium ferrite, while being the only known simple ferrites in which the ferric ions are found exclusively in the octahedral interstices, are at the same time the only non-magnetic ones. Obviously, therefore, there must be some connection between these two facts, but it would take us beyond the scope of the present article to go more deeply into this, so that we will merely state that the presence of ferric ions in the tetrahedral spaces seems to be an essential condition for ferromagnetism.

As already remarked, the cubic ferrites in question can form mixed crystals in all proportions. It has been found that under favourable conditions mixed crystals of magnetic with non-magnetic ferrites — particularly zinc ferrite — may have very high values of initial permeability (μ_0). In table II the value of μ_0 is given for some simple ferrites, and in table III that of some mixed crystals obtained by adding zinc ferrite.

Table II

Ferrite	Initial permeability μ_0
FeFe_2O_4 (normal)	appr. 10
FeFe_2O_4 (stress-free)	appr. 70
CuFe_2O_4 (quenched)	appr. 70
MgFe_2O_4	max. appr. 10
NiFe_2O_4	max. appr. 10
CoFe_2O_4	scarcely > 1
MnFe_2O_4	max. appr. 250 but inconsistent

Table III

Mixed crystal	Initial permeability μ_0
$\text{CuFe}_2\text{O}_4 + \text{ZnFe}_2\text{O}_4$	appr. 1500
$\text{MgFe}_2\text{O}_4 + \text{ZnFe}_2\text{O}_4$	appr. 700
$\text{MnFe}_2\text{O}_4 + \text{ZnFe}_2\text{O}_4$	appr. 3000
$\text{NiFe}_2\text{O}_4 + \text{ZnFe}_2\text{O}_4$	appr. 4000

From suitably chosen and treated mixed crystals Philips have manufactured ferrites which are being marketed under the trade name "Ferroxcube", indicating the cubic structure of these substances. By varying their composition or the heat treatment different grades, denoted as "Ferroxcube" I, II, III, etc., are obtained with widely divergent properties. The technical uses of these ferrites will be mentioned farther on.

Special measures to obtain high permeability

High permeability is obtained when there is no more than a slight interaction between the minute elementary magnets and the crystal lattice of the substance. The energy of interaction found in the undisturbed lattice is called crystal anisotropy, and this is known to assume very low values round about the Curie point, i.e. the temperature at which the ferromagnetism of a substance disappears and gives place to paramagnetism. This phenomenon is turned to account in the manufacture of "Ferroxcube", the Curie point being lowered, by the addition of the non-magnetic zinc ferrite, from several hundred degrees Celsius to a level approaching room temperature.

As a rule, however, the crystal lattice is disturbed by internal stresses, due in part to magnetostriction. By magnetostriction is understood the spontaneous distortion occurring when the material is magnetised; it is said to be positive when under increasing magnetisation elongation takes place and negative when shrinking occurs.

The materials most suitable for obtaining very high permeability are therefore those showing little magnetostriction, provided care is also taken to keep the internal stresses low (annealing at high temperature; homogeneous cubic structure). It has been found quite simple to get this low value of magnetostriction, especially in the case of "Ferroxcube" III, due in part to the fact that by mixing different ferrites both positive and negative values of magnetostriction are easily obtained. By mixing in the correct proportions magnetostriction can in fact be reduced to almost nil.

Condition for a high specific electric resistivity

Magnetite, Fe_3O_4 , has the comparatively low specific electric resistivity of 10^{-2} ohm cm (at room temperature). Other ferrites in which the ferrous ion has been replaced by another bivalent metal ion have a specific resistance of the order of 10^5 - 10^7 ohm cm. In cases, however, where only a small part of these metal ions are ferrous ions a specific resistivity of 10^2 - 10^4 ohm cm. is found.

Consequently in order to reach the highest possible resistivity the presence of ferrous ions should be avoided. For all practical purposes it is not necessary that they should be entirely absent, because a value of say 100 ohm cm. is no objection for a core thickness of about 1 cm and frequencies up to about 10^6 c/sec.

The low specific resistivity of Fe_3O_4 has been ascribed to the fact that both ferrous and ferric ions appear in the same kind of interstices in the crystal lattice. Such an explanation is plausible if it is assumed that an electron is taken from a ferrous ion and added to a ferric ion, so that the former becomes ferric and the latter ferrous. Since both kinds of ions are in fact present in similar places such an interchange does not essentially alter the structure. This means that such a displacement of electrons may easily occur, or in other words there is a considerable conductivity.

Losses and quality of coils

Separation of the losses

In the foregoing we have seen that it is possible to compound ferrites having a high permeability and a high specific electric resistivity. Thanks to the latter property the eddy current losses will generally be small, but these are not the only losses occurring, as was apparent from the experiments with Hilpert's materials. And in nearly all the uses to which coils are put the total losses of energy in the coils have some influence upon the properties of the oscillatory circuit or the filter of which the coil forms a part. These losses, therefore, call for some further consideration.

The total losses in a coil through which an alternating current is flowing with an angular frequency $\omega = 2\pi f$ can be accounted for in a replacement diagram by assuming a resistance R to be connected in series with a self-induction L . This loss resistance comprises in the first place the direct current resistance of the coil increased by a factor due to "skin effect", and further a part representing the dielectric losses, whilst finally another part corresponds to the magnetic losses. Since, however, we are only concerned here with the last mentioned losses the other two parts of R can be left out of consideration, so that in the following R represents only the magnetic losses.

The magnetic losses are made up of three components: eddy current losses, hysteresis losses and residual losses. It is possible that the last mentioned are related to the so-called after-effect phenomena⁴).

It is important to consider the ratio of R to the product of the permeability μ , the frequency f and the self-induction L . This ratio, the significance of which will be explained below, can be agreed with the above-mentioned division of the magnetic losses by writing it as follows:

$$\frac{R}{\mu f L} = c_h B_{\max} + c_e f + c_r(f) \dots (2)$$

Here the hysteresis losses are represented by the

hysteresis constant c_h (a material constant) multiplied by the maximum induction $B_{\max}$, whilst the eddy current losses are represented by the product of the frequency f and a factor c_e depending not only on a material property (e.g. specific resistance) but also on the shape and dimensions of the core — for instance for a core with circular cross-section (diameter D cm).

$$c_e = \frac{\pi^3}{2} \cdot \frac{D^2}{\rho} \cdot 10^{-9} \text{ sec.} \dots (3)$$

The residual losses are represented by the term $c_r(f)$, which depends upon the frequency.

Signification of the quantity $R/\mu f L$

The left-hand member of eq. (2) can also be written in the form:

$$\frac{R}{\mu f L} = \frac{2\pi}{\mu} \cdot \frac{R}{\omega L} = \frac{2\pi}{\mu} \cdot \frac{1}{Q} = 2\pi \cdot \frac{\tan \delta}{\mu} \dots (4)$$

in which Q is the so-called quality factor and δ the angle of loss. Thus the expression $R/\mu f L$ appears to differ only by a factor 2 from the quantity $(\tan \delta)/\mu$, which is of importance when determining the effect of an air-gap in the magnetic circuit (the application of an air-gap is an easy means of adjusting the self-induction of a coil). If L is the self-induction of a coil on a closed core of a material with permeability μ , and L' the self-induction obtained by applying an air-gap in the original core, then for the latter core (incl. air-gap) an "effective" permeability μ' can be taken, defined by:

$$\mu' = \frac{L'}{L} \mu.$$

If δ is the loss angle of the original coil and δ' that of the coil with air-gap, it can be deduced with fair approximation that

$$\frac{\tan \delta}{\mu} = \frac{\tan \delta'}{\mu'} \dots (5)$$

Strictly speaking $(\tan \delta)/\mu$ is not invariable but

$$\frac{\tan \delta}{\mu(1 + \tan^2 \delta)} \dots (6)$$

Since, however, only low values of $\tan \delta$ are of interest (small in comparison to unity), in practical use $\tan^2 \delta$ with respect to unity can be ignored. If, moreover, one has to do with values of μ or μ' that are large in comparison to unity, the expression (6) will not differ appreciably from the approximated form (5).

From equation (5) it follows that a reduction of μ to μ' is accompanied by a proportional reduction of $\tan \delta$, that is to say there is a raising of the quality factor (Q). The gain to be obtained in this

⁴) Philips Techn. Review, 8, 57, 1946 (No. 2)

way is all the greater according as the original permeability is higher.

In principle the same applies, it is true, to dust cores, where the high permeability μ of the insulating layers results in a low effective permeability, but — apart from the more favourable behaviour at high frequencies — the homogeneous "Ferroxcube" material has the advantage over dust cores in three important respects:

- 1) one is quite free in selecting the air-gap most favourable for each individual case; the dust core, on the other hand, has as it were a "built-in", air-gap, which cannot be made smaller;

highest level at which the material is useful for practical purposes, and for "Ferroxcube" III — the permeability of which is about 1000 — the frequency limit lies at approximately $0.5 \cdot 10^6$ c/sec.

In the case of ferrites the losses are usually formed for the greater part of the residual losses. Investigations carried out with the object of finding materials with a higher frequency limit had therefore to be directed primarily towards lower residual losses. It was found, however, that this could only be attained at the cost of permeability. In many cases it appeared, for instance, that whereas the absence of ferro-ions was favourable in respect

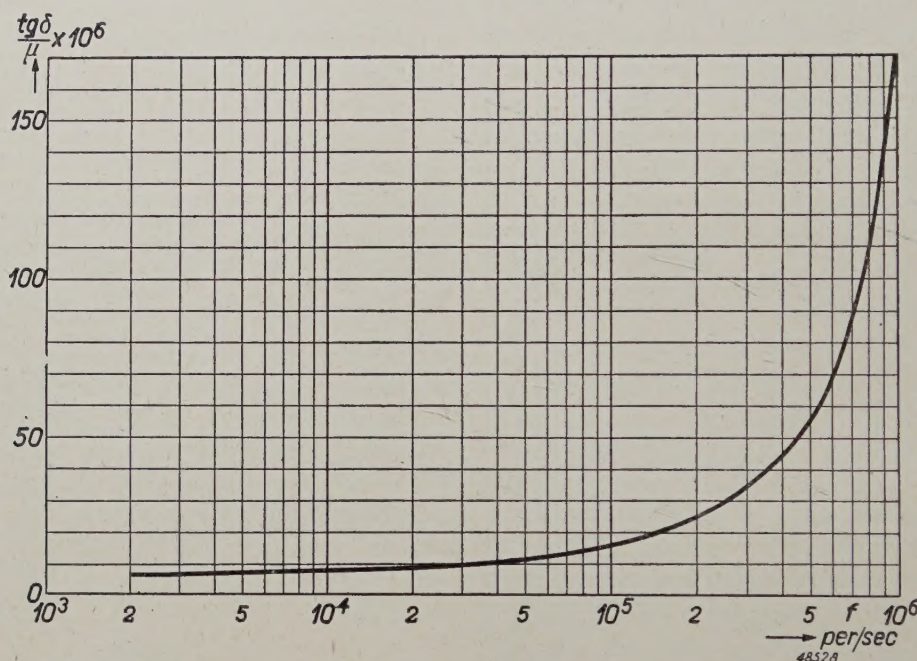


Fig. 1. The quantity $(\tan \delta)/\mu$ as function of the frequency f for "Ferroxcube" III. The permeability of this material is about 1000. The frequency limit where $\tan \delta$ reaches $6 \cdot 10^{-2}$ lies at about $0.5 \cdot 10^6$ c/s.

- 2) a much more effective magnetic screening can be obtained than with the heterogeneous dust core material (this will be reverted to when dealing with the application of "Ferroxcube");
- 3) the magnetic induction in the homogeneous "Ferroxcube" is much more uniformly distributed than in the grains of a powder core; this is favourable for arriving at low hysteresis losses.

Loss angle as function of frequency

In fig. 1 the quantity $(\tan \delta)/\mu$ of "Ferroxcube" III is set out as a function of the frequency. It will be noted that with rising frequency it first increases gradually and later at a faster rate. The frequency at which $\tan \delta$ reaches $6 \cdot 10^{-2}$ is regarded as the

to residual losses at high frequencies, for a high permeability their presence was essential. The highest frequency limit so far reached, about $40 \cdot 10^6$ c/sec, was obtained with a nickel-zinc ferrite having an initial permeability of about 50 and containing no ferrous ions.

Shaping and mechanical properties

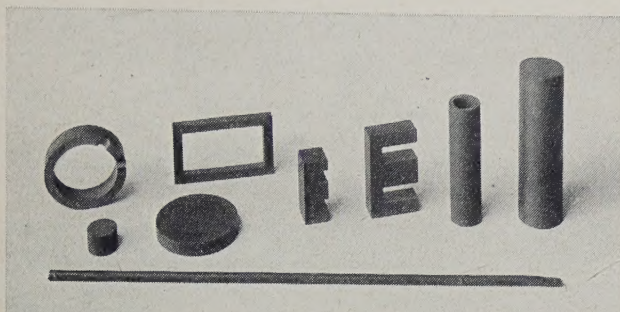
Before proceeding to deal with some of the applications of "Ferroxcube" we will briefly mention something about its manufacture.

Simple forms such as discs, rings, cubes and the like are made by compressing the powdered base material in the dry state in steel moulds.

Long, cylindrical shapes (rods or tubes of different diameters) are obtained by mixing the powdered

material with a binder to form a plastic mass, which is then forced through an aperture of the size required.

The objects turned out in this manner are then annealed in an electric oven to temperatures be-



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Fig. 2. Some specimens showing the shapes in which component parts of "Ferroxcube" can be made. The disc, ring and E-shaped pieces are moulded by dry compression of the basic material in powder form; the rod and tube-shaped pieces are formed by adding a binder to the powder and pressing the mass through a circular opening.

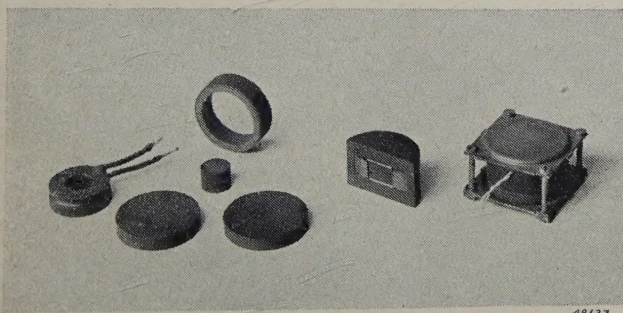
tween 1000 °C and 1400 °C, the binding agent used for plasticising thereby evaporating and the chemical reaction taking place through diffusion.

The heated product has a greater hardness but by grinding and polishing can be brought exactly to the desired dimensions. Fig. 2 shows some samples.

Practical applications

Band-pass coils for carrier wave telephony

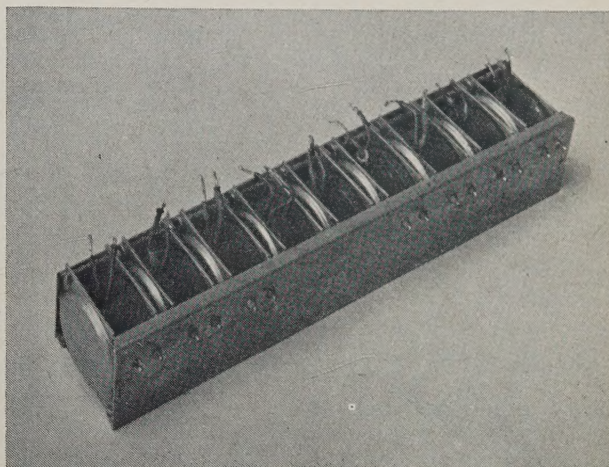
One of the most important components of a carrier wave telephony installation is the electric band-pass filter⁵⁾, the purpose of which is to avoid cross-talk. Only very low losses are admissible in the constituent parts of these filters (coils and condensers). "Ferroxcube" III is eminently suit-



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Fig. 3. Band-pass filter coil for carrier wave telephony. Extreme left: the winding and next to that the core and jacket parts made of "Ferroxcube". Farther to the right: a section of the jacket, core and winding: the two air-gaps have been filled with a small white plate to show them up better. Extreme right: the complete coil.

able as magnetic core material for the coils. Furthermore the constancy of the effective permeability with time and under temperature fluctuations has been proved to satisfy the high demands of practice. Fig. 3 shows a filter coil made of "Ferroxcube". The coil proper is enveloped by a sort of box of "Ferroxcube" consisting of two discs and a ring, whilst inside the coil is a small cylinder of the same material with an air-gap at each end, thus reducing the original permeability from about 1000 to an effective permeability $\mu = 35$. The box-like construction ensures a good magnetic screening, enabling a number of coils to be built together into a compact unit without risk of mutual inductance (cross-talk) - see fig. 4. The assembled coil has a quality factor $Q = 600$ (at a frequency of 60 kc/sec) and a volume of 44 cm³, both of which figures compare very favourably with those of a coil of the older construction (fig. 5) with $Q = 220$ and a



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Fig. 4. The coils required for one band-pass filter (here nine) can be built together into a compact whole. Thanks to the good screening provided by the "Ferroxcube" jacket (see fig. 3) there is no perceptible mutual inductance.

volume of 210 cm³. When comparing these figures it is to be borne in mind that with properly constructed coils Q is proportional to the linear dimensions.

Band-pass filter coil for the I.F. part of receiving sets

In radio sets built on the superheterodyne principle a signal of a fixed frequency, called the intermediate frequency, is obtained by mixing the incoming signal with an auxiliary signal generated in the set itself. A filter provides for a band of the desired width to be passed through that lies on either side of this intermediate frequency.

By using "Ferroxcube" the coils for these band-pass filters can be made of much smaller volume, as may be seen from fig. 6; this is most welcome to

⁵⁾ Philips Techn. Review, 7, 104, 1942.

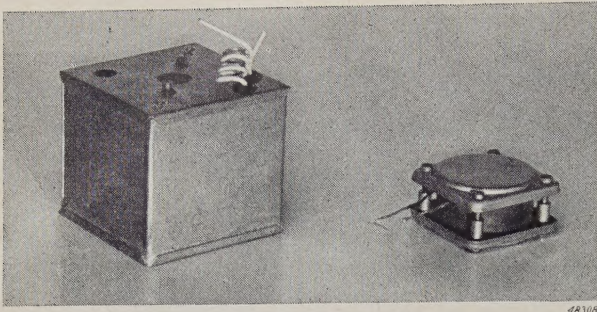


Fig. 5. Band-pass filter coils for carrier wave telephony. Left: screening cage containing a coil of the old construction with the core composed of filaments of nickel-iron and the jacket of a "powder-core" material. The screening is necessary owing to the low effective permeability of the powder core material. Quality factor $Q = 220$ at 60 kc/sec, volume 210 cm³. Right: coil with core and jacket of "Ferrocube" (cf. figs. 3 and 4); $Q = 600$ at 60 kc/sec, volume 44 cm³.

set-makers aiming at producing the smallest possible sets.

Other uses

It may be asked whether "Ferrocube" is also suitable for the cores of transformers connected to lighting or power mains. Generally speaking the answer is in the negative, because ferrites are saturated already at low inductances, of say 2500 gauss, and consequently the core diameter or the number of windings, for instance, would have to be at least five times as large as that required for the usual transformers with iron core, working with $B_{\max} =$ appr. 12 000 gauss.

There are, however, plenty of possibilities in other directions, such as:

- 1) the tuning of oscillatory circuits, either by sliding a "Ferrocube" core inside the coil (or coils) or by adjusting the effective permeability by means of d.c. magnetisation;
 - 2) applications in the technics of frequency and impulse modulation;
 - 3) for obtaining a more concentrated magnetic field in an object to be heated by induction in a magnetic alternating field of high frequency.
- It should be evident that this new material opens up an extensive field for investigation.

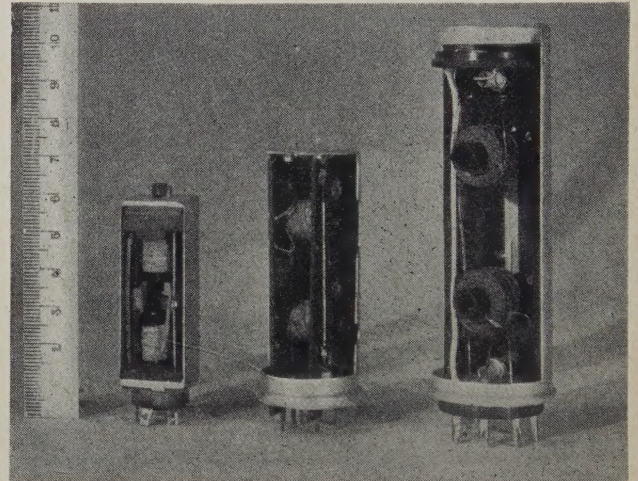


Fig. 6. Coil systems of the I.F. band-pass filter of a radio receiving set. The right-hand coil system contains no ferromagnetic material; the smaller dimensions of the other two are due to the use of "Ferrocube". The left-hand coil system is a further development of the middle one. All three coil systems are used for the same frequency and are of the same quality. Part of the screening has been cut away to show the inside.

A MAGNETRON FOR D.C. VOLTAGE AMPLIFICATION

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621.385.16: 621.385.831

In D.C. voltage amplification an amplifier valve with grid control (for instance a triode) often cannot be used because the input and output circuits can never be kept galvanically separated. Instead a magnetron can be used, *i.e.* a diode controlled by a magnetic field. The input circuit of a magnetron, being that circuit of which the solenoid setting up the magnetic field forms a part, is galvanically entirely separate from the anode circuit. In this article the magnetron is discussed as an amplifier valve. It is found that the magnetic sensitivity of a magnetron, which plays a part analogous to the amplification factor of a triode, can be considerably increased by introducing a grid at cathode potential close to the anode. As an example the employment of such a magnetron with grid is described in an X-ray apparatus where a regulator triode, at a very high voltage, had to be fed by a weak D.C. voltage signal given by a regulator at earth potential.

Triode and magnetron as amplifier valves

The simplest method of amplifying an electric signal is based in many cases on the use of a triode. The amplifying action of the triode is manifested in the fact that small changes in the grid voltage caused by the signal result in large changes in the anode voltage. These changes in the anode voltage are the direct result of the changes in the anode current, which is here controlled by an electric field due to the signal. However, for a long time there have been electronic valves in which the anode current is controlled by a magnetic field due to the signal and which can also be used as amplifier valves. While the triode may be considered as a diode with a grid between cathode and anode, the magnetron¹⁾ is a diode which is placed in the magnetic field of a solenoid whose axis is perpendicular to the direction of the electron current (if the diode is for instance cylindrical the axis of the solenoid coincides with the cathode). Changes in the current in the solenoid then cause changes in the intensity of the magnetic field, which again affects the motion of the electrons between the cathode and anode, whereby with suitably chosen conditions changes in the intensity of the anode current may occur. We shall discuss this in more detail below; it will be found that for a magnetron as well as for a triode quantities such as slope and internal resistance can be defined and that, moreover, a quantity can be introduced which is comparable with the amplification factor in a triode, namely the so-called magnetic sensitivity.

For the amplification of electrical signals the

triode (or tetrode or pentode) is nearly always used, and not the magnetron. There are, however, cases where the triode and also every other valve with grid control is inadequate and where the magnetron is the ideal valve. This is connected with the fact that in every valve with grid control the average voltage level to be used for the grid compared with the voltage level of the anode and of the cathode is fixed within rather narrow limits by the characteristics of the valve. In particular the voltage difference between the anode and the grid of a triode in the commonly used types cannot amount to more than a few hundred volts. As long as it is desired to amplify an A. C. voltage this involves no essential limitation of the usefulness of valves with grid control, even when the voltage level of the amplified signal has to lie much higher than that of the original signal. By making use of a transformer or of condensers provision can be made for the voltage difference between the anode and the grid not to exceed the above-mentioned permissible value. In the case of D.C. voltage amplification this is impracticable. It is indeed possible to apply a voltage difference between the input and output circuits which is within the limits permitted by the characteristic, but there is always a galvanic coupling between the two circuits which may be an objection. On the other hand in the case of a magnetron the input circuit (the solenoid) can be kept galvanically absolutely separate from the output circuit (the anode circuit), so that even with D.C. voltage amplification the above assumed difference between the voltage levels of the incoming and outgoing signals presents no difficulty.

A concrete example in which the magnetron has proved serviceable for the above reason occurred in an X-ray apparatus. At the conclusion of this article several particulars of this will be given.

¹⁾ It should be noted that the word "magnetron" is used in its original significance, namely that of a magnetically controlled diode, while at the present time "magnetron" usually means an oscillator valve for very short waves, where the electrons move in a constant magnetic field. Cf. G. Heller, Philips Techn. Rev. 4, 201, 1939.

Principle of the magnetron

The "classical" magnetron (see fig. 1) is a cylindrical diode (anode voltage V_a , anode radius r_a), situated in an axial magnetic field H generated by a solenoid.

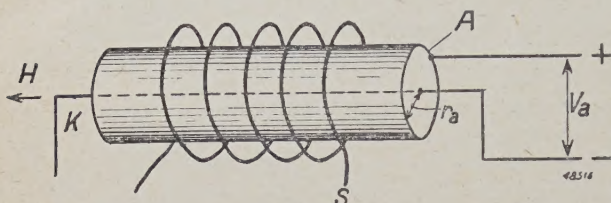


Fig. 1. Diagram showing the principle of a magnetron. A anode, K cathode, S solenoid. The arrow indicates the direction of the magnetic field H .

When only the electric field is present the electrons emitted by the cathode will describe radial trajectories to the anode; the electric field is radially directed. The velocity v of an electron at a given point is determined by the voltage V prevailing at that point (calculated with respect to the cathode). If m is the mass and e the charge of the electron

$$\frac{1}{2}mv^2 = eV \dots \dots \dots (1)$$

If we consider only the magnetic field, an electron with velocity v experiences a force perpendicular to the velocity and to the direction of the field and equal to evH . This results in the trajectory becoming curved; the kinetic energy of the electron undergoes no change due to the magnetic field since the force is perpendicular to its trajectory. The energy equation (1) thus does not change when in addition to the electric field we also introduce a magnetic field.

The force evH is equal to the centrifugal force mv^2/r , where r is the radius of curvature of the trajectory:

$$\frac{mv^2}{r} = evH \dots \dots \dots (2)$$

If now an electric field and a magnetic field are both applied, the electrons describe curved trajectories whose radius of curvature at every point can be calculated as a function of H and V by eliminating the velocity v from (1) and (2):

$$r = \frac{1}{H} \sqrt{\frac{2mV}{e}} \dots \dots \dots (3)$$

or, substituting the values of m and e and expressing r in cm, H in gauss and V in volts:

$$r = \frac{3,37}{H} \sqrt{V} \dots \dots \dots (3a)$$

With a given electrical voltage V we now vary the magnetic field strength H . At a small value of H the electrons move almost radially along only slightly curved paths from the cathode to the anode (see fig. 2a), since with a small value of H the value of r is very large, according to formula (3a). An anode current then flows, and as H increases it remains constant as long as the electrons emitted by the cathode reach the anode. As the value of H increases r decreases, and the paths of the electrons become more and more curved until, beginning with a critical field strength H_k , the electrons no longer reach the anode (see fig. 2b and 2c); there is no longer any anode current and the magnetron is "closed". If the cathode is sufficiently thin this critical field strength H_k can easily be calculated. It may then be assumed that the potential is constant in the larger part of the cylindrical space

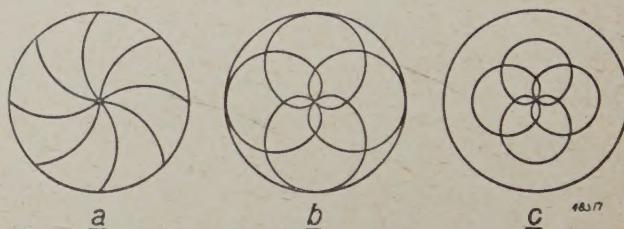


Fig. 2. Electron trajectories in a magnetron at different magnetic fields H : a) when $H < H_k$ anode current flows; b) $H = H_k$, the limiting case where the paths of the electrons just touch the anode; c) when $H > H_k$ the electrons describe closed trajectories and do not reach the anode.

enclosed by the anode, and that it is equal to the anode voltage V_a . The decrease in the potential toward the cathode occurs mainly in its immediate vicinity.

The electrons will then, according to (3a), describe paths with almost constant radius of curvature, thus approximately circles. The diameter $2r$ of these circles at the critical field strength H_k is equal to the radius r_a of the anode. With (3a) this gives

$$H_k = \frac{6,74}{r_a} \sqrt{V_a} \dots \dots \dots (4)$$

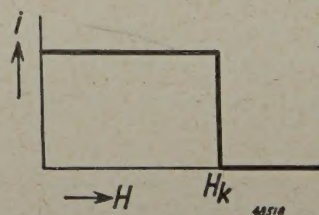


Fig. 3. "Magnetic" characteristic of an ideal magnetron, i.e. anode current as a function of the magnetic field strength at a single given value of V_a . At another value of V_a the vertical part of the characteristic is shifted towards the right or left.

The magnetic characteristic $i = i(H)$ at a single given value of V_a is shown in *fig. 3*. For $H > H_k$ the anode current is constant, all electrons reaching the anode; for $H < H_k$ the current is “cut off”. According to (4) H_k depends on V_a : if V_a increases, H_k also lies at a higher value.

The magnetic sensitivity of the magnetron

As is known, the slope S and the internal resistance R_i of a triode are defined by the equation

$$\Delta i = S \Delta V_g + (1/R_i) \Delta V_a, \dots (5)$$

where Δi , ΔV_g and ΔV_a are the changes, respectively in anode current i , grid voltage V_g and anode voltage V_a . From equation (5) it follows that

$$S = \left(\frac{\partial i}{\partial V_g} \right)_{V_a} \dots \dots \dots (6)$$

and

$$R_i = 1 / \left(\frac{\partial i}{\partial V_a} \right)_{V_g} \dots \dots \dots (7)$$

Moreover, the amplification factor μ is defined as

$$\mu = - \left(\frac{\partial V_a}{\partial V_g} \right)_i \dots \dots \dots (8)$$

or, because of (5),

$$\mu = S R_i \dots \dots \dots (9)$$

Since in the magnetron the function of the grid voltage is taken over by the magnetic field, the “magnetic” slope and the internal resistance are here defined by analogy with equations (6) and (7) by

$$S = - \left(\frac{\partial i}{\partial H} \right)_{V_a} \dots \dots \dots (10)$$

and

$$R_i = 1 / \left(\frac{\partial i}{\partial V_a} \right)_H \dots \dots \dots (11)$$

(In the definition (10) of S the minus sign is taken because the anode current i decreases as H increases.)

Equation (9) then defines for the magnetron a quantity which is analogous to the amplification factor in the case of a triode. This quantity will be called the “magnetic sensitivity” of the magnetron. The magnetic sensitivity, however, in contrast to the amplification factor of a triode, is not a dimensionless factor. This is seen immediately when the magnetic sensitivity is represented by the formula analogous to (8):

$$\mu = \left(\frac{\partial V_a}{\partial H} \right)_i \dots \dots \dots (12)$$

It is now found that equation (9) fails us in the case of an ideal magnetron with a discontinuous magnetic characteristic (*fig. 3*). Then the electrical characteristic (*fig. 4*) of the magnetron, i.e.

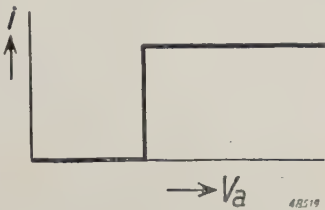


Fig. 4. “Electrical” characteristics of an ideal magnetron, i.e. anode current as a function of the anode voltage at a single given value of the magnetic field H .

$i = i(V_a)$, with a given magnetic field H is also discontinuous; at small values of V_a the influence of the magnetic field is predominant, the electrons describe closed trajectories and $i = 0$; at large values of V_a which — see equation (4) — are larger than $(Hr_a/6.74)^2$, the anode draws all the electrons. By reference to figures 3 and 4 it may be seen that in the horizontal part of the characteristics $S = 0$ and $R_i = \infty$, while in the vertical parts $S = \infty$ and $R_i = 0$, so that in the ideal case the magnetic sensitivity defined by (9) cannot be determined from the characteristics.

A similar consideration shows that also equation (12) cannot be used in this ideal case.

In order to calculate the magnetic sensitivity of an ideal magnetron, however, there are two indirect methods. One is to consider a non-ideal magnetron for which the characteristics show a gradual change. The quantities S and R_i are then always finite, so that the product $S R_i$ is no longer indeterminate. It is then possible to calculate $\mu = S R_i$ and ascertain the limiting value of the magnetic sensitivity (thus calculated) when the shape of the characteristics no longer approaches

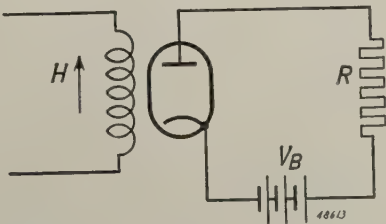


Fig. 5. The magnetron in a circuit for resistance amplification.

the ideal. The other possibility is based upon the consideration of an ideal magnetron included in a resistance amplifier. We shall first follow this second method, since it will also lead us to a knowledge

of the behaviour of the magnetron in its practical applications.

Magnetron in a resistance amplifier

Let us consider the simple resistance amplifier with an ideal magnetron as amplifier valve (fig. 5). We wish to study the relation between the voltage V_R over the anode resistance R and the magnetic field H . For that purpose we draw the electrical

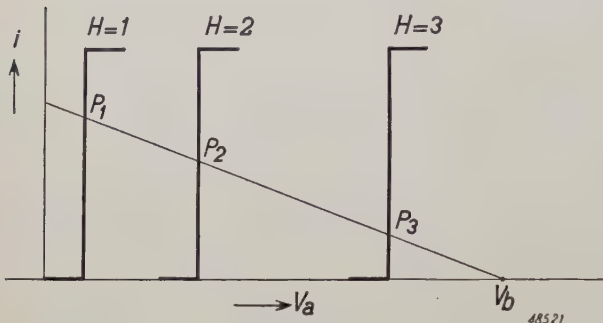


Fig. 6. Vertical part of the electrical characteristic (cf. fig. 4) for different values of the magnetic field H (in arbitrary units). The oblique straight line represents the "loading line", i.e. the relation between the anode current i and the voltage V_a when the magnetron is included in a circuit of a resistance amplifier with given battery voltage V_b and anode resistance R . The slope of the loading line is inversely proportional to R . The points of intersection $P_1, P_2, \dots$ of the loading line with the characteristics determine the current flowing in the anode circuit at given values of V_b and R and different values of H .

characteristics of the magnetron, i.e. i as a function of V_a for different values of the magnetic field (fig. 6) (this is analogous to the i - V_a diagram with V_g as parameter in the case of a triode). It is hereby assumed that the diode is ideal, i.e. that for $H = 0$ the saturation current already flows at very small positive anode voltage. We allow the characteristics to be cut by the "loading line", i.e. by the straight line

$$i = \frac{V_b - V_a}{R},$$

which gives the relation between i and V_a at a given battery voltage V_b and resistance R . The points of intersection of the loading line with the characteristic determine the current flowing in the anode circuit at given values of H , V_b and R .

By choosing suitable values of R and V_b , i.e. of the slope and position of the loading line, the current can be made to adjust itself on the vertical sections of the characteristics. We also assume that this is actually the case. Then the relation between V_a and H (see equation (4)) is given by:

$$V_a = \left(\frac{r_a}{6,74} \right)^2 H^2. \dots (13)$$

By elimination of V_a we obtain the following from the last two equations:

$$i = \frac{1}{R} \left[V_b - \left(\frac{r_a}{6,74} \right)^2 H^2 \right]. \dots (14)$$

The desired relation between V_R and H is thus

$$V_R = V_b - \left(\frac{r_a}{6,74} \right)^2 H^2. \dots (15)$$

The parabola given by equation (15) is reproduced in fig. 7. It may be seen that V_R decreases with increasing H and for $H_b = 6.74 \sqrt{V_b/r_a}$ becomes zero. The slope of the parabola may serve as a measure of the amplifying effect of the resistance amplifier considered and is analogous to what in a triode is called the "amplification" of a resistance amplifier.

In the case of a triode — as is known — the amplification becomes equal to the amplification factor when the internal resistance R_i is small compared with the anode resistance R . By analogy to this the slope in question becomes equal to the above-defined magnetic sensitivity, since for the ideal magnetron, in the vertical parts of the characteristics of fig. 6, $R_i = 0$. One thus obtains

$$\mu = - \frac{dV_R}{dH}. \dots (16)$$

(since dV_R/dH is always negative — compare fig. 7 — in equation (16) the minus sign is taken). From this it now follows that, according to (15) and (13)

$$\mu = 2 \left(\frac{r_a}{6,74} \right)^2 H = \frac{r_a}{3,37} \sqrt{V_a}. \dots (17)$$

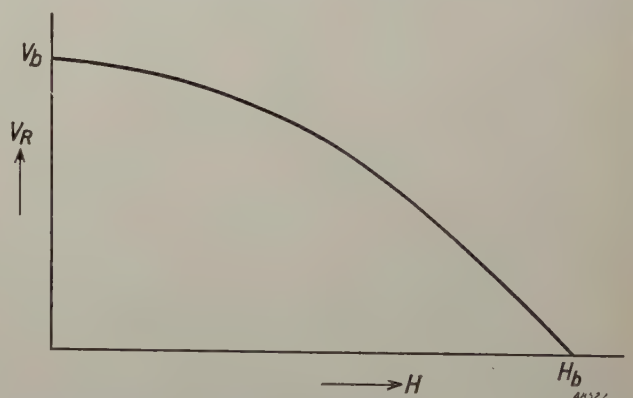


Fig. 7. Voltage V_R over the anode resistance as a function of the magnetic field H for a resistance amplifier with an ideal magnetron. For $H = 0$, V_R is equal to the battery voltage V_b ; for $H = H_b = 6.74 \sqrt{V_b/r_a}$ (r_a radius of the anode), $V_R = 0$. The curve is a parabola with slope equal to the magnetic sensitivity μ of the magnetron.

We shall find this result again by the other method mentioned above. From equation (17) it is found that the magnetic sensitivity increases proportionally with the strength of the magnetic field.

The maximum value of the magnetic sensitivity at a given battery voltage is

$$\mu_{\max} = \frac{r_a}{3,37} \sqrt{V_b}.$$

Magnetron with gradually varying characteristic

Actually a magnetron is never ideal. Since the electric field is not strictly radially and axially symmetrical, and also due to the fact that the vacuum in the valve is not perfect, the characteristics are not discontinuous (fig. 8). Thus, for

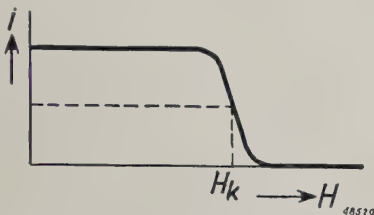


Fig. 8. Gradually varying magnetic characteristic (compare with fig. 3). H_k is here defined as that value of H where $i(H_k) = \frac{1}{2} i(0)$.

example, the electric field at the ends of the anode may be too weak to draw the electrons to the anode, while in the middle electrons *do* strike the anode. The shape of the characteristics is thus less sharp, since the anode current does not become zero at one definite value of V or H .

In the case of a magnetron with gradually changing characteristics the product $\mu = SR_i$ is no longer indeterminate. We shall now calculate it on the assumption that the characteristics, while not discontinuous, still have a steep slope.

We may then define H_k as the field strength at which the current has decreased to one half: $i(H_k) = \frac{1}{2} i(0)$. For H_k thus defined equation (4) will remain approximately valid. For the neighbourhood of H_k we may write, in approximation, according to equation (10):

$$i(H) = i(H_k) - (H - H_k) S(H_k),$$

and from this, since

$$1/R_i = \left(\frac{\partial i}{\partial V_a} \right)_H = \left(\frac{\partial i}{\partial H_k} \right)_H \frac{dH_k}{dV_a},$$

it follows that

$$1/R_i = \left\{ \left(\frac{\partial i(H_k)}{\partial H_k} \right)_H + S(H_k) - (H - H_k) \left(\frac{\partial S}{\partial H_k} \right)_H \right\} \frac{dH_k}{dV_a}.$$

In general the first and last terms of the polynomial between the brackets are small compared with $S(H_k)$.

An estimation of the first term can be made on

the basis of the following consideration. If we are working in the saturation region, $\partial i(0)/\partial H_k = 0$. If we are not working in the saturation region, since according to Langmuir's formula $i(0) \sim V_a^{3/2}$, $i(H_k) \sim V_k^{3/2}$ also, and with (4) this gives: $i(H_k) \sim H_k^3$, from which it follows that

$$\left(\frac{\partial i(H_k)}{\partial H_k} \right)_H = \frac{3 i(H_k)}{H_k}.$$

If now the slope is so large that

$$\left| \left(\frac{\partial i}{\partial H} \right)_{V_a} \right| \gg \frac{3 i(H_k)}{H_k},$$

or, according to fig. 9 that $\tan \gamma \gg \tan \beta$ we may indeed ignore the first term between the brackets. From fig. 9 it appears that only at large values of β (i.e. small values of H_k and V_a) is this not the case.

The last term between the brackets is zero for $H = H_k$ and remains small in the vicinity of that point.

For not too small values of V_a and H_k it thus follows that

$$1/R_i = S(H_k) \frac{dH_k}{dV_a} \dots \dots (18)$$

and the magnetic sensitivity is then (see equation (9)):

$$\mu = S(H_k) R_i = \frac{dV_a}{dH_k} \dots \dots (19)$$

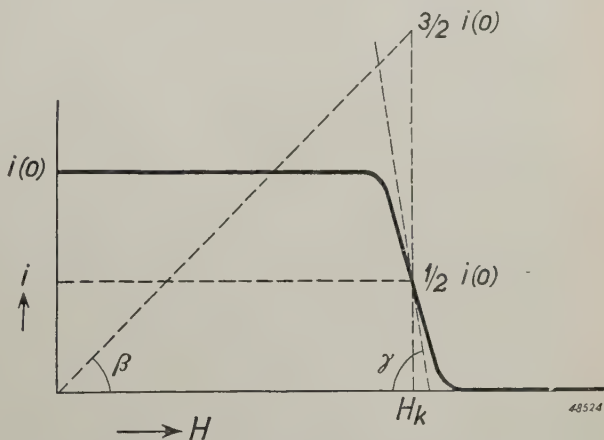


Fig. 9. Magnetic characteristic of a magnetron; when $\tan \beta \ll \tan \gamma$ formula (20) for the magnetic sensitivity is valid.

Upon comparison of (19) with (8) it is found that dV_a/dH_k in the case of the magnetron is similar in significance to $-(\partial V_a/\partial V_g)_i$ in the case of the triode.

With the help of equation (4) it is now possible to calculate dV_a/dH_k , so that one finally obtains

$$\mu = 2 \left(\frac{r_a}{6,74} \right)^2 H_k = \frac{r_a}{3,37} \sqrt{V_a} \dots \dots (20)$$

The magnetic sensitivity is thus independent of the slope of the magnetic characteristic. From this it follows in particular that equation (20) is also valid for the limiting case of an ideal magnetron with a discontinuous characteristic. This formula is indeed identical with the formula which we previously derived for the ideal magnetron in a resistance amplifier (see equation (17)). The only advantage of a very steep magnetic characteristic is that then, according to (9), R_i is small. Since in a resistance amplifier $R_i \ll R_a$ (R_a anode resistance) in order to reach the maximum amplification a relatively small value of R_a will be sufficient.

Magnetron with grid

If it is desired to increase the theoretical magnetic sensitivity we must, according to equation

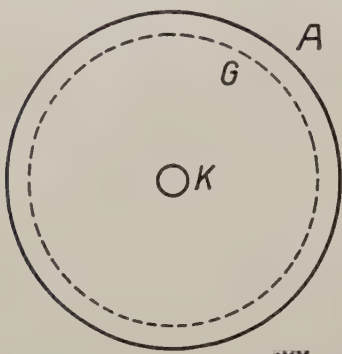


Fig. 10. In order to increase the magnetic sensitivity μ , a grid is introduced into the cylindrical magnetron close to the anode. K cathode, G grid, A anode.

(2), either increase the anode voltage or the radius. The first has the objection that the magnetic field has also to be taken larger: one must work with a large constant field upon which the variations are superposed. The increase in the radius quickly leads to unwieldy dimensions.

It is possible to attain a much higher sensitivity, without encountering the two difficulties mentioned, by placing close to the anode (fig. 10) a grid which is at approximately cathode potential. The influence of the anode voltage on the motion of the electrons between the cathode and the grid is then much smaller, so that the magnetic field has relatively more effect. Instead of equation (4), the following then holds:

$$H_k = \frac{6,74}{r_a} \sqrt{V_{eff}}, \quad \dots \quad (21)$$

where V_{eff} is an effective voltage which — entirely analogous to the so-called effective grid voltage in a triode — can be represented by

$$V_{eff} = \frac{V_a}{G} + V_g; \quad \dots \quad (22)$$

the constant G in the triode with screen grid being equal to the amplification factor. For the sake of simplicity we set $V_g = 0$. Equation (21), because of (22), then becomes

$$H_k = \frac{1}{\sqrt{G}} \frac{6,74}{r_a} \sqrt{V_a} \quad \dots \quad (23)$$

We shall now consider the magnetron with grid included in a resistance amplifier. Proceeding in the same way as in the case of an ideal magnetron with no grid, we arrive at the following relation between V_R and H :

$$V_R = V_b - G \left(\frac{r_a}{6,74} \right)^2 H^2. \quad \dots \quad (24)$$

From fig. 11 we see that the curve giving this relation is steeper than the analogous curve for the magnetron with no grid, which corresponds to equation (15). The magnetic sensitivity has thus indeed become larger, namely by a factor G with the same magnetic field and the same radius of the anode, as appears upon differentiation of equation (24):

$$\mu = - \frac{dV_R}{dH} = 2G \left(\frac{r_a}{6,74} \right)^2 H. \quad \dots \quad (25)$$

The anode voltage must now be higher, but that is often no objection. The value of G is limited by the requirement that the value of V_a/G must be large enough to draw a reasonable current from the cathode. As to the optimum dimensions, these depend upon the employment of the valve. Compared with the simple magnetron, however, considerable gain can nearly always be obtained for instance with a factor $G = 20$.

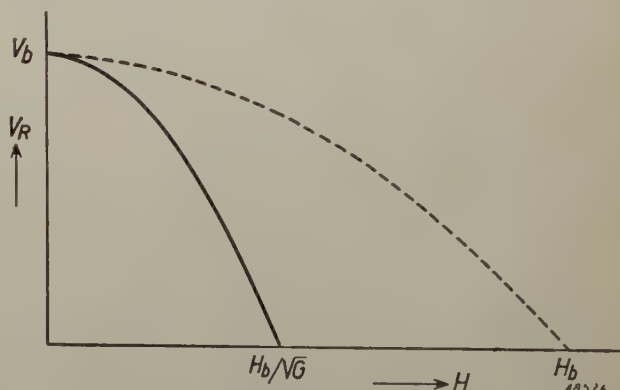


Fig. 11. Voltage V_R across the anode resistance as a function of the magnetic field H for a resistance amplifier. 1) with a grid-magnetron (continuous line), 2) with an ideal magnetron with no grid (dotted line, identical with the curve of fig. 4). Both curves are parabolas. Since the magnetic sensitivity μ is equal to the slope of the parabola, at equal values of H , μ is larger in the first case than in the second.

It may still be noted that equation (25) can also be derived on the basis of the consideration of a magnetron with gradually (but steeply) changing characteristics.

Magnetron with grid as D.C. voltage amplifier in an X-ray apparatus

Such a magnetron with grid has been employed in the above-mentioned X-ray apparatus. The problem encountered in designing the apparatus in question came down to the question of how a switching and regulating arrangement at a very high voltage (about 100 kV) could be operated by a weak D.C. voltage signal given by a switching and regulating arrangement at earth potential. Various solutions to this problem are of course possible, but a discussion of all these is outside the scope of this article.

It need only be noted that the use of an amplifier valve with grid control was out of the question because of the reasons mentioned above, at least if it was desired to avoid the conversion of D.C. into A.C. and *vice versa*. On the other hand the employment of the grid-magnetron was found to

be very suitable. A simplified circuit diagram of the installation is reproduced in *fig. 12*. It may be seen that the voltage level of the solenoid *S* is completely separated from the very high voltage level of the rest of the installation; the latter can be varied at will without affecting the circuit in which the solenoid is included. Nevertheless, the grid voltage of the triode *T* changes as soon as a change occurs in the current in the solenoid. The grid voltage in question is equal to the voltage over the resistance *R*, and the latter voltage depends finally on the current in the solenoid.

We may regard the triode *T* as a variable resistance whose value R_T is determined in part by the current in the solenoid. When no current flows through the solenoid the magnetic field is zero, the magnetron is "open" and the triode "closed", i.e. $R_T = \infty$, because the grid voltage is then equal to the full (negative) battery voltage V_b . If on the other hand the current through the solenoid is so large that the strength of the magnetic field lies above the critical value $H_b/\sqrt{G}$ (cf. *fig. 11*), then the magnetron is "closed"; as a result the voltage over *R*, and thus also the grid voltage, is zero: the triode is entirely "open", i.e. $R_T = 0$. At currents in the solenoid which lie between the limiting values mentioned, $0 < R_T < \infty$.

If the triode is used as relay it means that only the values $R_T = 0$ and $R_T = \infty$ are used. In the X-ray apparatus of *fig. 12*, however, the triode also served as regulator valve with which the voltage on the X-ray tube *Rö* was regulated; R_T then followed the changes in the current in the solenoid, between the limits $R_T = 0$ and $R_T = \infty$ ²⁾.

The advantage of a magnetron with grid was thereby manifested in the fact that in both cases — triode as regulator valve and as relay — much weaker currents were needed in the solenoid to reach a given change in R_T than if a magnetron with no grid had been used. If the triode plays only the part of a relay, the solenoid current necessary to "open" the triode completely (change from $R_T = \infty$ to $R_T = 0$) is $\sqrt{G}$ times as small as in the case of the magnetron with no grid.

²⁾ If the saturation current flows through the X-ray tube, not too large changes in R_T will have no influence on the current in the X-ray tube, only the voltage being affected.

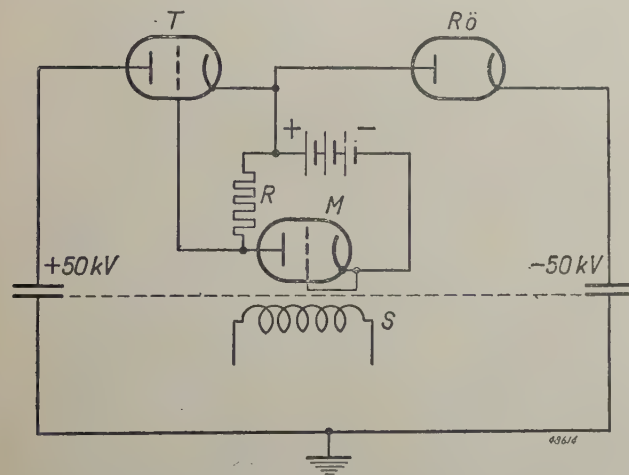
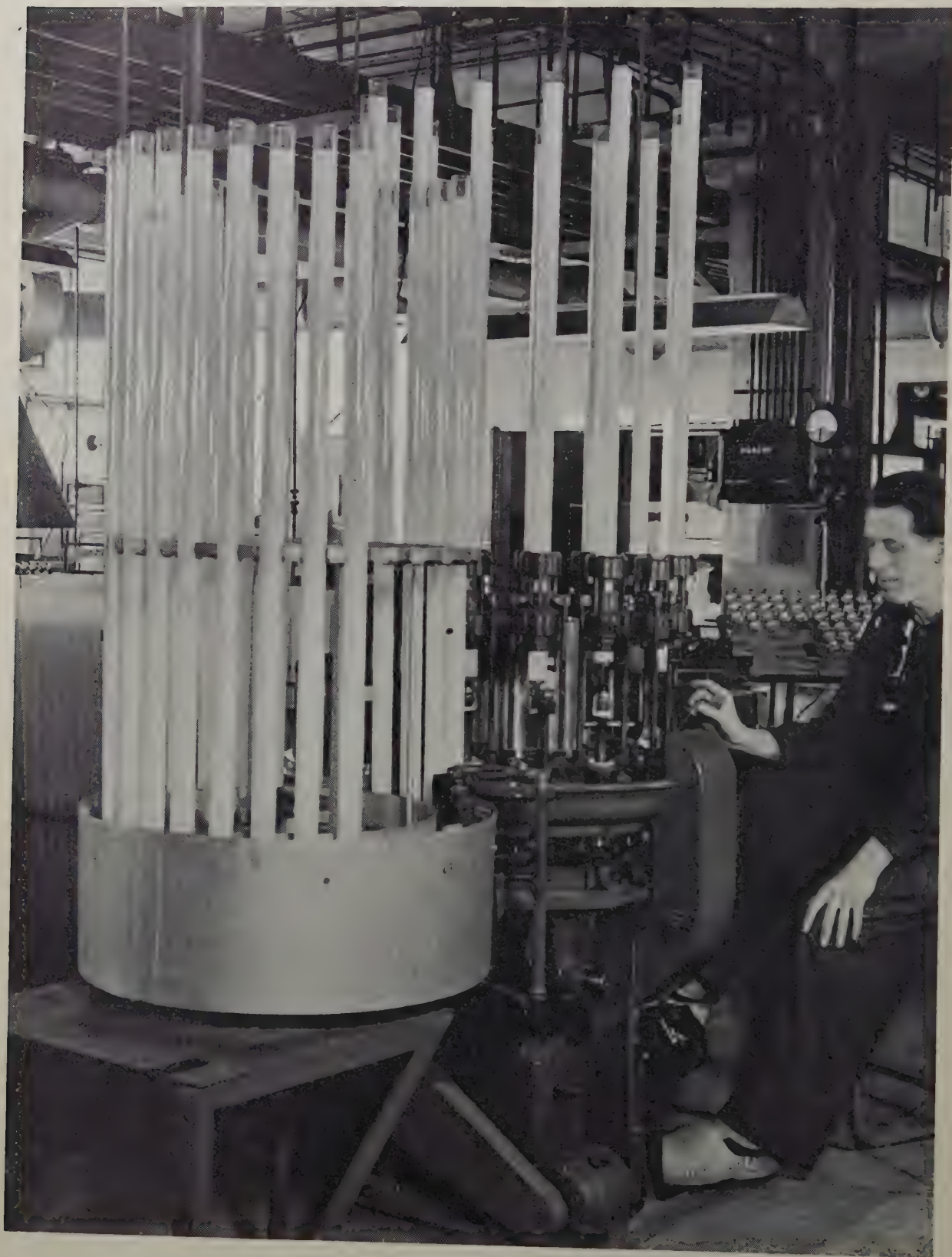


Fig. 12. Simplified circuit diagram of an X-ray apparatus in which the grid magnetron serves as amplifier valve. *T* triode regulating the voltage on the X-ray tube *Rö*. The voltage difference between grid and cathode of *T* is equal to the voltage across the resistance *R*; the variations in this latter voltage are due to the amplification of the voltage variations in the circuit in which the solenoid causing the magnetic field is included. This magnetic field regulates the current in the grid magnetron *M*. When no current flows through the solenoid, the magnetron is "open" and the triode "closed". The horizontal dotted line indicates symbolically that the voltage level below this line (i.e. the voltage level of the circuit of the solenoid) is entirely independent of the voltage level above it.

AUTOMATIC SEALING- IN OF THE ELECTRODES IN TUBULAR FLUORESCENT LAMPS



The tube is placed over a preheated, mounted electrode on a rotating machine (centre) which automatically seals the two together by gradually increased heating of the rims. The tubes are then transferred to a cooling drum (left) in which the sealed ends are gradually cooled down. The same process is repeated with the tubes inverted, for sealing in a mounted electrode at the other end, after which the tubes are ready for evacuation.

ABSTRACTS OF RECENT SCIENTIFIC PUBLICATIONS OF THE N.V. PHILIPS' GLOEILAMPENFABRIEKEN

Reprints of the majority of these papers can be obtained on application to the Administration of the Research Laboratory, Kastanjelaan, Eindhoven, Netherlands. Those papers of which no reprints are available in sufficient number, are marked with an asterisk.

- 1697:** N. G. de Bruyn: A combinatorial problem (Proc. Kon. Ned. Akad. Wetenschappen Amsterdam **49**, 758-764, 1946).

A P_n -cycle is defined as an ordered cycle of 2^n digits 0 or 1 (i.e. a series of such digits placed on the circumference of a circle), such that the 2^n possible sets of n consecutive digits of that cycle are all different (as a consequence, any ordered set of n digits 0 or 1 occurs exactly once in that cycle). Posthumus, studying these cycles in connection with a practical problem of telecommunication, was led to the conjecture, that the number of P_n cycles be equal to 2 to the power $2^{n-1}-n$. In this paper this conjecture is proved to be correct. As a consequence a theorem concerning a special type of networks is stated and proved and another application of the theorem is mentioned.

- 1698:** D. Polder and J. H. van Santen: The effective permeability of mixtures of solids (Physica, 's-Grav. **12**, 257-270, 1946).

For several purposes it is of importance to know how the dielectric or magnetic permeability of a mixture of substances, which show mutually different permeabilities in pure state, depends on the composition of the mixture. In this paper the case is dealt with, where the different substances are powders of solids, packed in a medium like oil or wax or air. The individual particles or holes are assumed to be ellipsoidal. The calculation is based on an approximation, which in the case of spherical particles proves to give results identical with those obtained by Böttcher's method. The effect of the shape of the ellipsoids is discussed. Considerations are given concerning the nature of the approximations used in this paper and in other theories on this subject.

- 1699:** M. J. O. Strutt and A. van der Ziel: Signal-noise ratio at v.h.f. (Wireless Engineer **23**, 241-249, 1946).

The two basic concepts of correlation between fluctuation currents and voltages and of the decompositions of fluctuating quantities into singly periodic components are discussed briefly. The noise ratio of a grounded-cathode amplifier is evaluated and the conditions for minimum noise ratio are stated. Experimental evidence is shown to confirm

the theoretical results. Further grounded-grid amplifier stages and velocity modulation valves are considered and the requirements as to valve construction (uniform electron paths and low dielectric and other losses) are dealt with. It is shown that the purposed reduction of noise ratio applies also to wideband reception. In order to compensate the loss or gain incurred by the reduction of noise ratio suitable feed-back may be applied. The interrelation of noise figures introduced by various authors and the present noise ratio are discussed.

- 1700:** B. D. H. Tellegen: Het bepalen van de integratieconstanten bij de berekening van in- en uitschakelverschijnselen (T. Ned. Radiogenootschap II, 173-188, 1946). (The evaluation of the integration constants occurring in the computation of transient phenomena).

A network is considered containing a source of pressure v , under the influence of which a current i flows in a certain branch. A method is given to calculate from the differential equation connecting i and v the discontinuities in i and its derivatives resulting from discontinuities in v and its derivatives.

- 1701:** H. A. Klasens: Transfer of energy between centres in zinc sulphide phosphors (Nature, **158**, 306, 1946).

The transfer of energy between centres in zinc sulphide phosphors containing two kinds of centres (e.g. blue and green) is explained by the supposition that after bringing an electron from one centre (e.g. blue) to an excited state (by lifting it in the empty so-called conduction band of energy), the hole in the blue centre may be transferred to a filled band and thus may travel to a green centre. The reverse process (green to blue) is supposed to have a negligible probability. The above hypothesis is expressed in the form of two simultaneous differential equations giving the number of excited centres as a function of time.

From these equations formulae may be derived for the intensity ratio of the blue and the green emission during irradiation as a function of the irradiation intensity and the temperature and for the temperature — dependence of the emission of

e.g. the blue centres. The effect of "killers" on the after glow (green emission) is explained on similar lines.

- 1702:** J. Boeke: Ontwikkeling van de elektrische meetapparaten in de chemie gedurende de oorlog. (Chem. Weekblad **42**, 230-273, 1946) (Development of electrical measuring instruments for chemical purposes during the war).

This article contains a survey of recent improvements in electrical methods as used in chemistry, especially in the following fields: Electrochemistry, dielectric constants, measurement of moisture, spectrometry (absorption and emission), chemical analysis, industrial apparatus.

- 1703:** W. de Groot: The influence of irradiation with light on the dielectric properties of ZnS phosphors (Physica **12**, 402-404, 1946).

Experiments are described, whereby the influence of irradiation with light on the light emission and the dielectric behaviour of ZnS phosphors are observed simultaneously. It is proved that the change in capacity ΔC of a condenser containing ZnS, and the decay of this change after stopping irradiation are much slower than the rise and decay of the light emission. Experiments are described, which, make probable that the change in dielectric behaviour is due to free electrons and not to trapped electrons. Some phenomena, such as a steep initial decay of the ΔC -effects with a phosphor containing a killer, remain unexplained.

- 1704*:** D. J. Bouma: Kleuren en kleurindrukken (Philips technische bibliotheek; uitg. Meulenhoff & Co N.V. Amsterdam 1946, 320 pages, 113 fig.) (Colours and colour sensations).

In this book (an English translation of which is forthcoming) a survey in simple language is given of the fundamentals of colour science and the methods of colorimetry. In the exposition of the basic facts ample use is made of colour space. Additional chapters deal with colour vision, the historical development of colour science, thresholds, the estimation of colour differences and related problems, technical and scientific applications. The appendix comprises 15 tables and an extensive reference list.

- 1705*:** H. A. Klasens and M. E. Wise: Decay of zincsulfide type phosphors (Nature, London, **158**, 483, 1946).

The bimolecular decay of zincsulfide phosphors, assuming retrapping in the metastable phosphorescence centra, is described by a second order non-linear differential equation. In the special case where the two unknown constants (α = retrapping coefficient, β = bimolecular recombination constant) are equal, the equation can be solved and curves may be drawn for the intensity *vs.* time at different temperatures and for different intensities of excitation. These curves generally display a steep initial decay due to the bimolecular recombination and a more or less prolonged tail due to the phosphorescence mechanism.

- 1706:** C. J. Bouwkamp: A note on singularities occurring at sharp edges in electromagnetic diffraction theory. (Physica, 's-Grav. **12**, 467-474, 1946).

Wave functions u describing the diffraction by plane screens can be divided in two classes according as u or $\partial u / \partial n$ vanishes at the surface of the screen. Differentiation with respect to the coordinate in the *n*(ormal)-direction alters the character, whilst tangential differentiation does not change the class. Another effect (Rayleigh) of differentiation is the appearance of singularities at the edge of the screen. This is demonstrated explicitly in case of Sommerfeld's solution of the electromagnetic diffraction by a half-plane. Typical difficulties in electromagnetic diffraction theory are mentioned. Möglich's solution of the electromagnetic diffraction by a circular screen is shown to be erroneous.

- 1707:** W. Elenbaas: The hypothesis of minimum voltage in the theory of the arc. (Physica, 's-Grav. **12**, 491-498, 1946).

The author criticizes the explanation of the contraction of the high pressure discharge in the vicinity of the cathode making use of the theory of minimum voltage. Although this theory and the exact theory may be put in such a form, that they yield very similar formulae, there is a discrepancy as regards the cross section of the arc by a factor which at ordinary current densities may be as high as 50 and which moreover depends on the temperature. At very high current densities (almost complete ionisation) the principle is considered to give good results.

SURVEY OF SUBJECTS VOLUMES 1-8

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